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Protecting Explorer XVI solar cells

Service lifetimes greater than a year in man-made radiation belts—even for the older-type P/N cells—are promised by relatively economical quartz "windows" made by a vapor-deposition method

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Reprint

Presence of an artificial radiation belt caused by the high-altitude nuclear explosion of July 9, 1962, presented a severe and essentially unanticipated radiation hazard to the solar cell power supply of the Explorer XVI Micrometeoroid Satellite. This hazard was demonstrated by the marked increase in the degradation rate of solar cells on Transit 4B and Traac satellites.[1] By September 1962, sufficient data had been assembled to make rough estimates of the properties of the new belt—primarily high-energy electrons with an approximate fission energy spectrum. An average flux of 7.4 by 10^{12} electrons/cm^2 per day was estimated by Goddard Space Flight Center for Explorer XVI in its predicted orbit.

There was inadequate time for complete redesign of the power supply to provide more capacity as an allowance for increased radiation damage, or to change to more radiation-resistant N/P solar cells. Fortunately, improvements in the Scout booster permitted the increased weight of additional shielding. An experimental program helped establish the additional window thickness required, and to qualify types of fused quartz that could be procured rapidly. Samples of the Explorer XVI solar cells and prospective shielding materials were irradiated with 1.2-Mev electrons, both by themselves as well as in combination, using the Langley Research Center electron accelerator. Total doses up to 2.7 by 10^{15} electrons/cm^2 (1 year at 7.4 by 10^{12} electrons/cm^2 per day) were employed.

A drawing of a typical Explorer XVI solar cell tray and its mounting arrangement, after the new 3/16-in.-thick windows were installed, is shown at the top of page 49. It will be noted the 1/8-in.-thick magnesium tray base, the 1/10-in.-thick aluminum heat-transfer band, and the vehicle itself, give adequate shielding in back of the cells. Prior to the increase in space radiation it was estimated that the output of the cells would be decreased approximately 12% in 1 year, due primarily to high-energy protons penetrating, but not darkening, the original 1/16-in.-thick fused quartz windows. This estimate was supported by tests.

The accelerator used in tests was a constant-potential, cascaded-rectifier type, Radiation Dynamics Model No. P.E.A.-1.0. The bottom figure on page 49 shows the experimental setup. The electron beam enters from the accelerator and is scanned vertically at a rate of about 10 cps by the scan magnets. Next, the beam passes through a 2-mil titanium window, blower cooled. The beam then travels about 4 in. in air to the tray where samples are mounted. The position of the beam was established by using polyvinyl chloride film which turns dark when irradiated. Uniformity of the beam intensity was measured through the use of cobalt glass dosimetry. An area of approximately 4 by 12 in. was found to be uniform to ±5%. Current density was monitored by using a 1- by 2-cm aluminum pickup which passed the current received through an electrometer to ground. In addition, the sample tray and support were grounded to prevent any change in their potential. The energy used in these tests, as measured by the extreme range of electrons in aluminum at location of the samples, was 1.2 Mev. Beam current density was held constant at 0.03 microamp/cm^2 in order to minimize heating effects. The measured temperature rise under these conditions was 5–8 F. Because of the small heating, no auxiliary sample cooling was employed.

The solar cells tested were nominally 8% efficient, P/N-type, and 1 by 2 cm in size. Four cells, randomly selected from those purchased for Explorer XVI, were used in each test. To simulate the actual vehicle mounting arrangement each cell was cemented to a 1/8-in.-thick Dow 17-coated magnesium strip with RTV-40 cement. When shields were employed, they were spaced the same distance above the cells as in the vehicle arrangement. During tests, the magnesium strips were directly attached to the aluminum sample tray. Before irradiation and after each dose, the cells were evaluated with the shields, if any, removed. Tungsten lights with filament temperatures at 2800 K were used, and the cell loading was varied from short circuit to open circuit. Spectral response curves were also obtained to relate the measurements to space sun.

The samples of transparent shielding materials were spaced 3/32 in. above the aluminum sample tray during tests involving only these materials. Before and after each irradiation dose a typical nonirradiated solar cell was used to measure the broad band per cent light transmission in the spectral range of interest with

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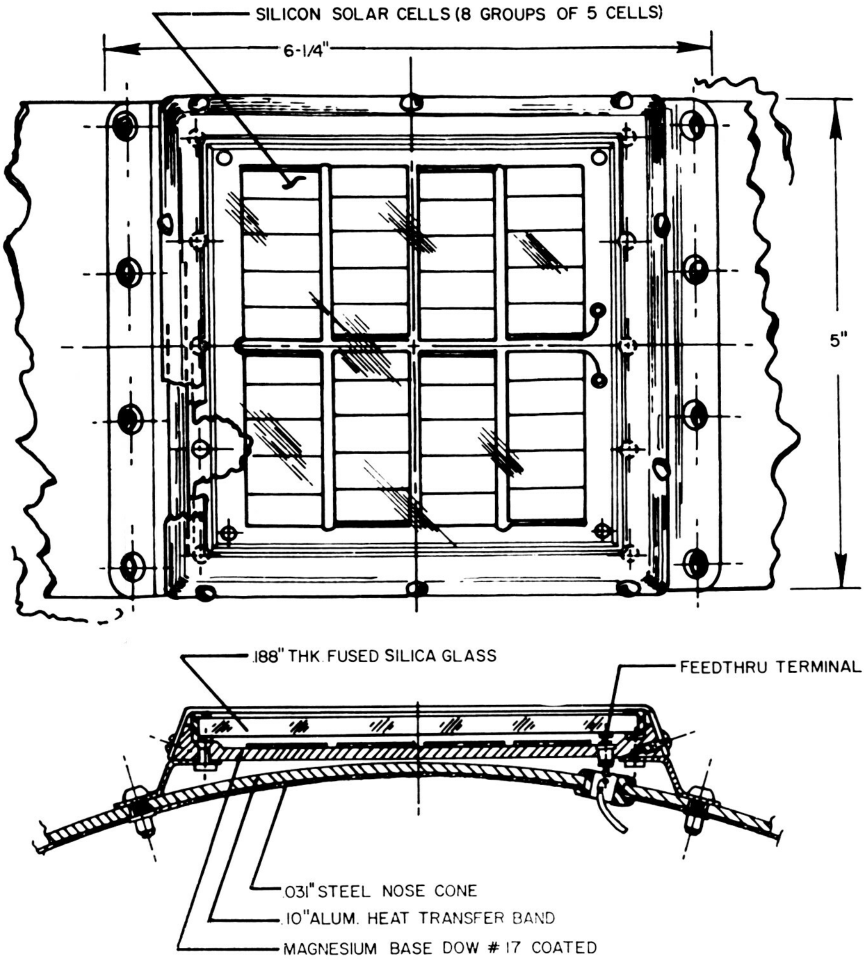
an accuracy of approximately 1/2%. Spectral transmission curves were also made over the spectral range of 4500–25,000 Angstroms.

The figure at the top of page 50 shows effect of electron irradiation at 1.2 Mev on the power output of bare and shielded solar cells. The per cent reduction of initial output power at 0.375 volt (corrected for the spectral distribution of space sunlight) is plotted as a function of total dose. Data are shown for the bare cells and for cells shielded with two different thicknesses of quartz. The curves are drawn through the average of the points for the four cells used in each test. Degradation of the bare cells approximated that obtained in previous Langley tests and that obtained by others for similar cells.[2] In this case, data were taken under conditions identical to those for the shielded cells.

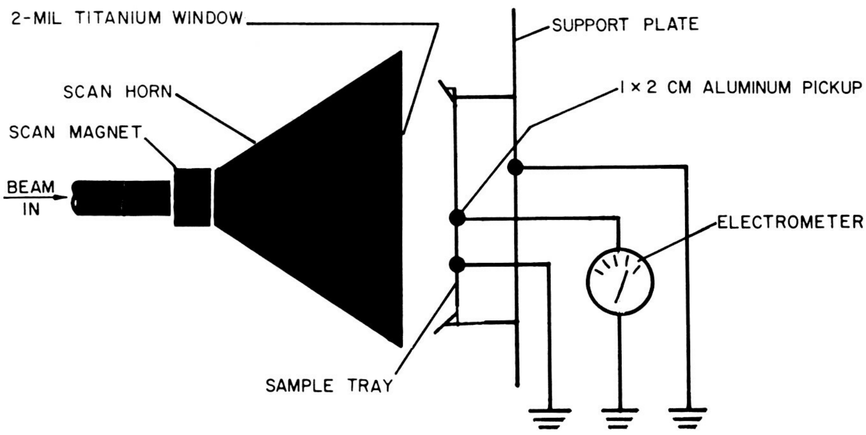
One feature that is surprising is the degree of damage done to the solar cell behind the 3/16-in.-thick quartz shield. The weight of this shield is 1.05 gm/cm^2 and it is quite adequate to stop all of the electrons used in this particular test. It will be observed that the average power output is reduced by about 7.5% at a total dose of 2.7 by 10^{15} electrons/cm^2. Unless scattering was considerably greater than expected, this degree of damage is surprising because the bremsstrahlung efficiency at this energy and in the relatively light silicon dioxide is quite low. Thus it may well be that the effectiveness of the bremsstrahlung radiation at this energy is greater than previously estimated.[2] As a practical result, this may mean it is impossible to completely protect an extremely radiation-sensitive type of cell. Also it should be noted that the degree of damage done to the cell shielded by 1/16-in.-thick quartz is not as great as would be expected. Range measurements indicate that there should be approximately 52% transmission through a 1/16-in.-thick quartz shield.[3] However, of this 52% that get through, it can be deduced from damage data that only about 3% arrive with energies sufficiently above the damage threshold.

The second surprising feature was the vast difference in darkening of four samples of similar quartzes under irradiation. Each had a different trade name but all were manufactured by fusing crystalline quartz, one being originally intended for Explorer XVI. With previous tests under proton irradiation simulating a 1-year dose, no darkening was observed. In the later tests, light transmission of this particular quartz was reduced by approximately 10%. (See photos on page 51.)

CONSTRUCTION OF TYPICAL SOLAR-CELL POWER UNIT



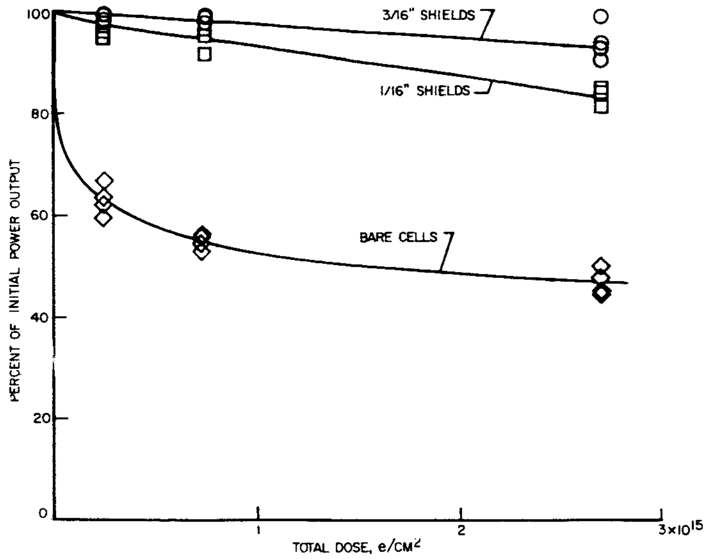
EXPERIMENTAL SETUP



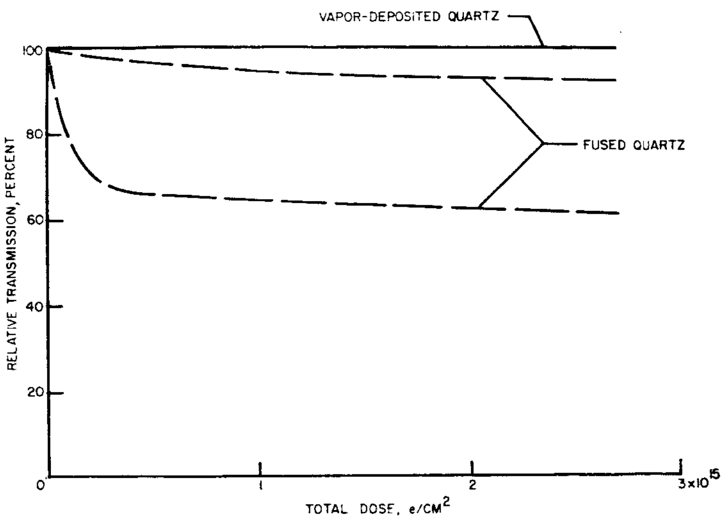
Note: Distance from titanium window to sample tray is about 4 in.

The middle figure shown on page 50 gives a more quantitative indication of the manner in which quartz darkens, and shows the change in light transmission as measured with a solar cell plotted against total dose. The particular curves shown do not correspond directly with photographic evidence of darkening; however, they are quite representative of the wide variety of the quartzes tested. It will be observed from the lowest curve that a quartz which will darken severely will do so very early during its exposure to electron radiation. Thus, a

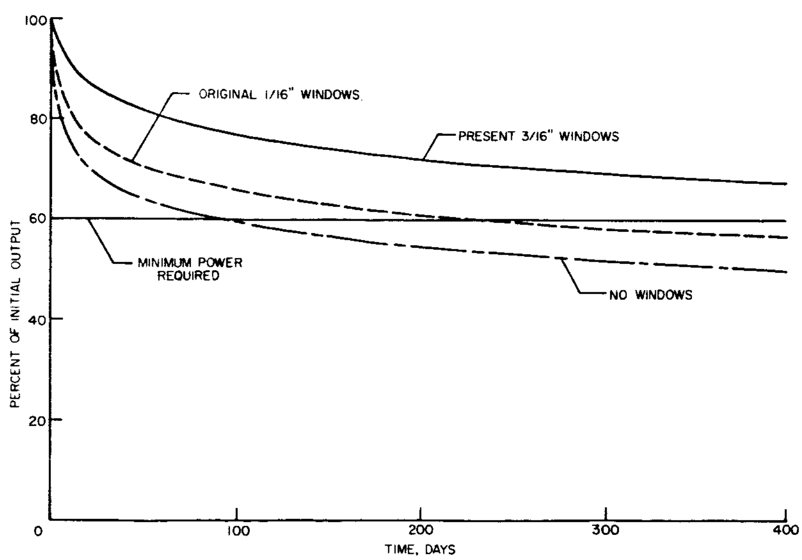
EFFECT OF 1.2-MEV ELECTRONS ON BARE AND SHIELDED CELLS



DEGRADATION OF QUARTZ WINDOW



SHIELDING EFFECT ON POWER-SUPPLY LIFETIME



short expected lifetime in space is not a suitable reason for selecting shielding material without reference to radiation sensitivity. In each case where darkening was noted, the spectral transmission curves indicated a broad absorption band centered at 5500 Angstroms.

A reasonably large number of quartzes were found which did not darken at all under irradiation. In each case these were made by a vapor deposition method and are often called synthetic fused quartz. The quartz finally chosen, Corning #7940, was selected primarily on the basis of rapid availability. Samples of sapphire such as used on Telstar were tested also and showed no degradation in light transmission. Reasons for use of quartz in preference to sapphire were that the design (already fixed) required larger pieces of shielding material than could be obtained in sapphire, and economy.

In translating the test results into lifetime in space, the following assumptions were made:

1. The average omnidirectional flux was 7.4 by 10^{12} electrons/cm^2/day.

2. The solar cells will be exposed to half the total flux because of the heavy shielding behind them. A geometric argument can be used to justify still another factor of 2, but this has not been used because the following assumption has already been shown to be unconservative.

3. Bremsstrahlung radiation has not been considered.

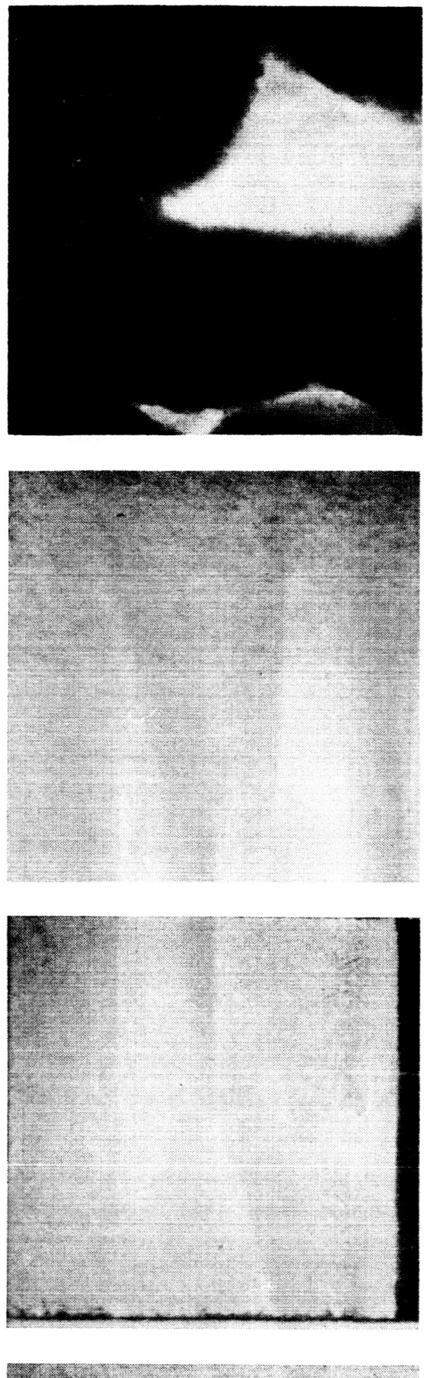
4. The fission energy can be used to represent the energy spectrum of all the electrons.

5. The fraction of electrons transmitted through 3/16-in. of quartz (1.05 gm/cm^2) is 1/13 and through 1/16-in. of quartz is 1/2.5.[4]

6. The solar cell damage rate is the same as that measured at 1.2 Mev.

The bottom diagram at the left shows the predicted decrease of initial output plotted against time for the bare cells as well as those with 1/16-in.- and 3/16-in.-thick quartz shields. The preceding assumptions and the above-described tests on the bare cells were used in preparing the figure. If the original 1/16-in. windows had been used, the solar cell output would probably have dropped to the minimum power required to operate the electronics before the expected lifetime of one year. With the present 3/16-in. windows, it can be seen that the solar cells will supply the required output for at least the expected lifetime.

On December 16, 1962, Explorer XVI was injected into an earth orbit with nearly the same parameters as the orbit used when estimating the ex-



Fused quartz test samples showing degrees of darkening after irradiation.
The sample at bottom originally was intended for use on Explorer XVI.

pected radiation dose. The actual orbital parameters were a perigee of 750 km, apogee of 1180 km, and inclination of 52 deg. On March 26, 1963, after 100 days in orbit, a test group of unprotected solar cells showed a degradation of approximately 30%. This compares with the predicted value of 40% as noted in the figure at bottom of page 50. At the same time, another test group of cells, protected with 3/16-in.-thick fused quartz windows in the same manner as the power cells, showed a degradation of about 20%, compared with the predicted value of 23% shown in the same figure.

The lower degradation is comforting, and can be at least partially explained. Some decay of the electron flux at the lower orbital altitudes of Explorer XVI has occurred. In March of 1963, Goddard Space Flight Center reestimated the flux encountered by Explorer XVI using data available at that time. An average dose of 2.3 by 10^{12} electrons/cm^2 per day was obtained, down by a factor of 3.2 from that originally estimated. If this flux value had been used to prepare our figure, a degradation of 33% would have been predicted for the unprotected cells—closer to that measured.

On basis of this study, the following general conclusions can be drawn:

1. It is possible to suitably protect even older type P/N cells to the point where service lifetimes greater than one year in the artificial radiation belt may be obtained.

2. Bremsstrahlung damage may possibly be greater than has been previously estimated, thus making it impossible to totally shield extremely radiation-sensitive solar cells.

3. Of the 1.2-Mev electrons that are transmitted through a 1/16-in.-thick quartz shield, only a small per cent get through with energy greater than the damage threshold of silicon.

4. Small differences in quartz make major differences in darkening under irradiation; however, the samples of synthetic fused quartz obtained from several manufacturers did not perceptually darken in the spectral range of interest.

5. Quartzes which darken severely do so in the early part of the dose.

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